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Noise propagation through open windows of finite depth into an enclosure

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2aNS8. Noise propagation through open windows of finite depth into an enclosure

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Predicting the insertion loss of an opening backed with an enclosed space is important for building noise control. Recent research in sound transmission through apertures of finite depth in infinite rigid baffles has included the effects of propagating and evanescent modes within the aperture in order to extend models to higher frequencies. The present study extends the model to the case of the aperture backed by a cavity as opposed to sound radiating into half-space. The role of coupling between the aperture modes, radiation modes, and cavity modes in the transmission was investigated. The results were compared to those of previous models which neglected the depth of the aperture and finite element modeling using COMSOL Multiphysics. Comparisons show that the current model is effective at predicting the sound transmission loss through the aperture and the acoustic field within the cavity for an obliquely incident plane wave. By changing impedance conditions on the half-space side of the aperture and within the aperture, the model has been used to evaluate passive noise control techniques.

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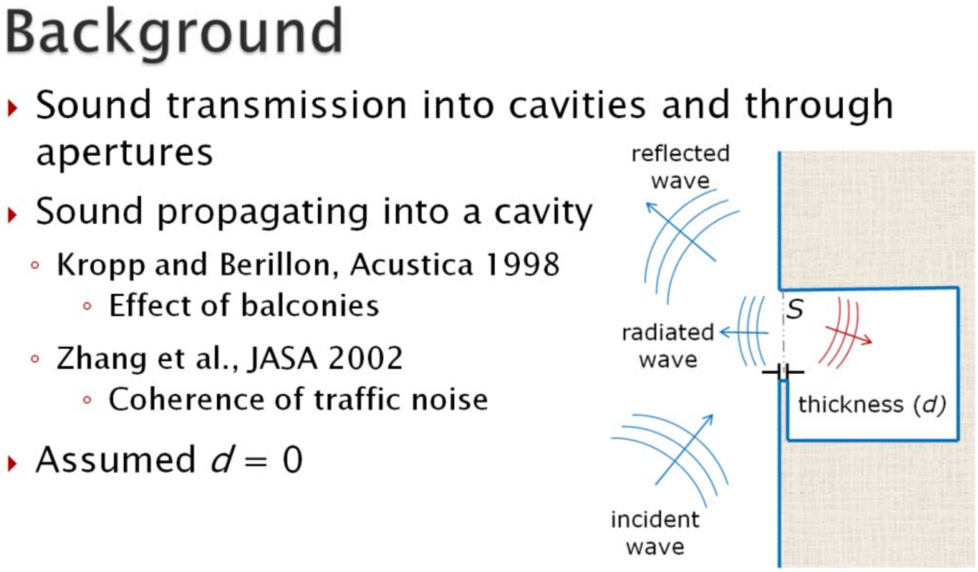
Included in this paper are slides that were presented for this talk in Cancun on November 16, 2010. The talk presented our approach to model sound propagation through open windows into a room. Our goal in this research is to develop a model that we can use to evaluate noise control techniques at low and mid frequencies for this situation.

Previous work has considered sound transmission into cavities or through apertures of finite thickness. Studies of sound propagating into a cavity have used the geometry pictured in Figure 1 consisting of a cavity with an opening, *S*, in an infinite rigid baffle. At the boundary, incident, reflected, and radiated waves are coupled to modes in the cavity. Kropp and Bérillon[1] studied the effect of balconies on noise transmitting into a room and found that at low and middle frequencies there were higher sound pressure levels at the back of the balcony due to resonance modes. Because the wall between a balcony and room is generally glass, which acts as a low pass filter, there would be an increase in sound transmission into the room at low and middle frequencies. Zhang *et al*.[2] studied the coherence of acoustic pressure on either side of the window due to traffic noise. His evaluation compared well to experiment indicating that it is reasonable to model noise control techniques for this situation. However, both of these studies assumed that the window was infinitely thin.

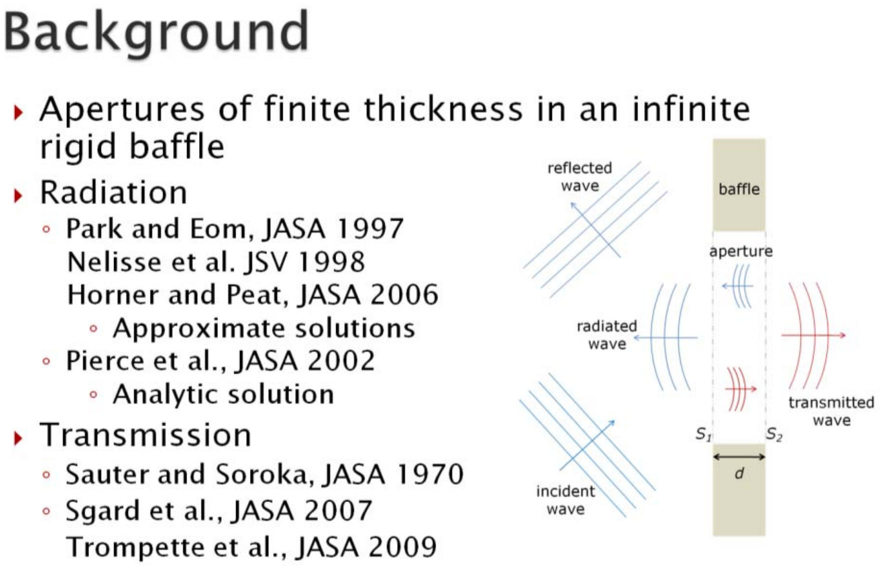


Background

- Sound transmission into cavities and through apertures
- Sound propagating into a cavity
  - Kropp and Berillon, Acustica 1998
    - Effect of balconies
  - Zhang et al., JASA 2002
    - Coherence of traffic noise
- Assumed $d = 0$

Figure 1. Previous work considering sound propagating into a cavity through an opening in an infinite baffle

Several studies have also analyzed the radiation and transmission of sound by an aperture set in a rigid, infinite baffle. The radiation from such an aperture is of particular interest because it is the most computationally expensive part the problem. Several approximations and numerical solutions have been proposed, [3-5] and an analytic solution has been developed by Pierce *et al*.[6] for an aperture backed by an arbitrary acoustic system. Sauter and Soroka[7] developed a theoretical relationship for the transmission of sound between two reverberant rooms, and Sgard *et al*.[8] developed a mathematical model for an aperture bounded on both sides by half-space. Experimental validation for this model was provided by Trompette *et al*.[10] As shown in Figure 2, this model consisted of incident, reflected, and radiated waves existing in half-space coupled to aperture modes through the surface S_1 ; the aperture modes were then coupled to a wave radiating into a second half-space through S_2.

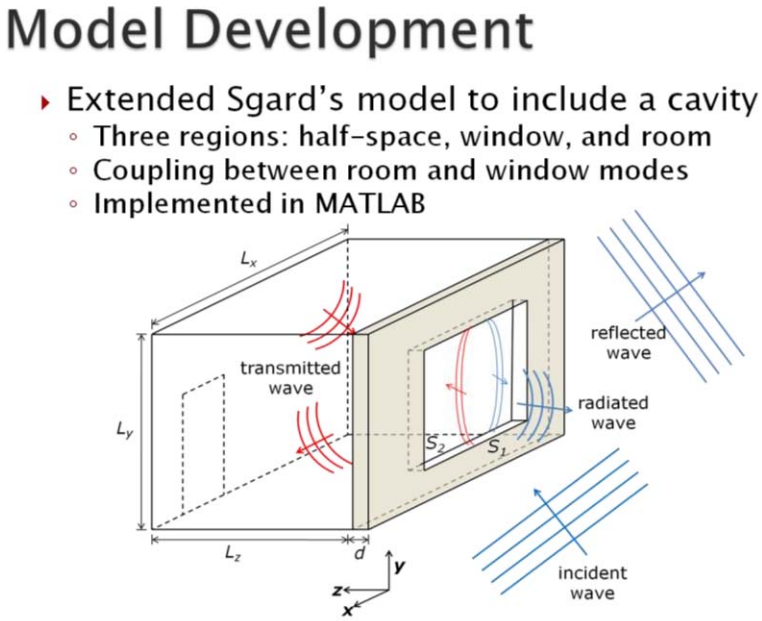


Background

- Apertures of finite thickness in an infinite rigid baffle
- Radiation
  - Park and Eom, JASA 1997
    Nelisse et al. JSV 1998
    Horner and Peat, JASA 2006
    - Approximate solutions
  - Pierce et al., JASA 2002
    - Analytic solution
- Transmission
  - Sauter and Soroka, JASA 1970
  - Sgard et al., JASA 2007
    Trompette et al., JASA 2009

Figure 2. Previous work considering sound transmission and radiation from an aperture of finite thickness

Our present model extends Sgard's model to include a rigid-walled cavity, room, coupled to the aperture modes through S_2, as shown in Figure 3. In half-space, there existed an obliquely incident plane wave, reflected wave, and radiated wave. Within the window of thickness d, waveguide modes (hereafter window modes) were assumed with waves traveling in the $\pm z$ directions. Similarly, the acoustic pressure distribution in the room was solved from waveguide modes (hereafter room modes) for traveling waves in the $\pm z$ directions and a rigid wall at $z = L_z + d$. The origin was centered on S_1. The wall baffling S_2 was accounted for in solving the boundary conditions at S_2, continuity of acoustic pressure and continuity of particle velocity. These boundary conditions were also solved at S_1. The resulting mathematical model was coded in MATLAB®.

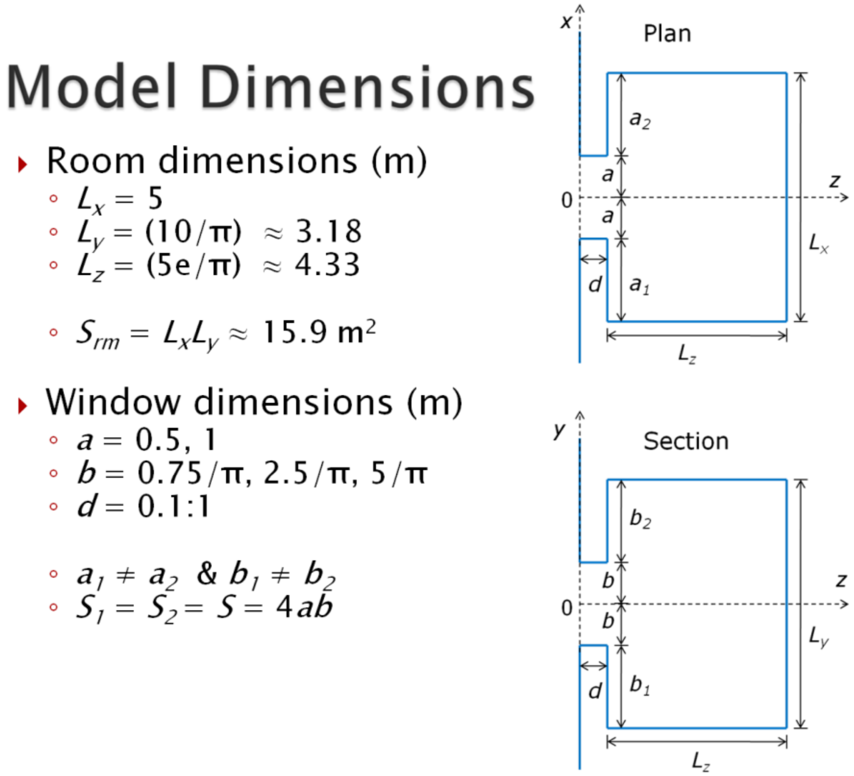


Model Development

- Extended Sgard's model to include a cavity
  - Three regions: half-space, window, and room
  - Coupling between room and window modes
  - Implemented in MATLAB

Figure 3. Present model, open window backed by a rigid-walled room

Figure 4 provides plan and section views of the present model's geometry and dimensions. Irrational values were used for room and window dimensions to avoid degenerate modes. The inequalities $a_1 \neq a_2$ and $b_1 \neq b_2$ were maintained so that the window would not be centered on the wall in either direction, which allowed for all room modes to be excited.

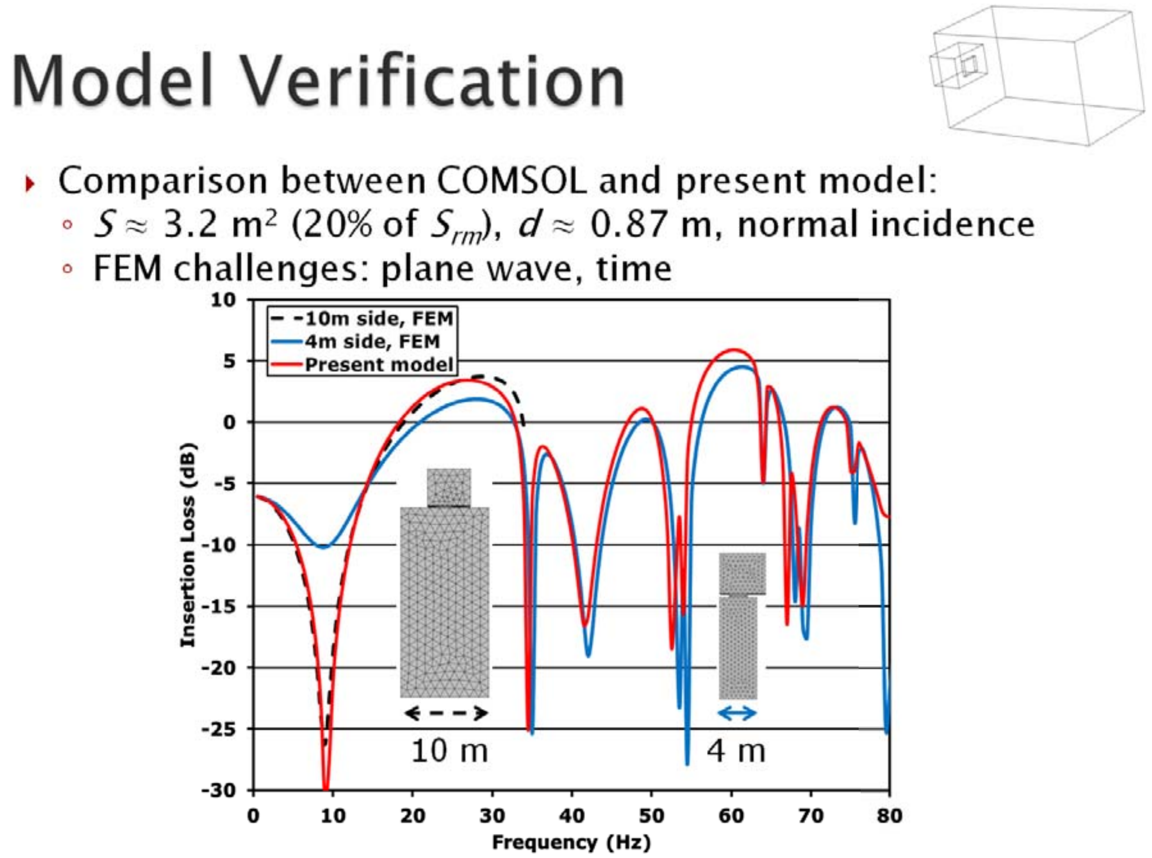


Model Dimensions

- Room dimensions (m)
  - $L_x = 5$
  - $L_y = (10/\pi) \approx 3.18$
  - $L_z = (5e/\pi) \approx 4.33$
  - $S_{rm} = L_x L_y \approx 15.9 \text{ m}^2$
- Window dimensions (m)
  - $a = 0.5, 1$
  - $b = 0.75/\pi, 2.5/\pi, 5/\pi$
  - $d = 0.1{:}1$
  - $a_1 \neq a_2$ & $b_1 \neq b_2$
  - $S_1 = S_2 = S = 4ab$

Figure 4. Geometry and dimensions of the present models

Our model was validated by calculating the insertion loss of the system, open window backed by a room, with our mathematical model and with the finite element method (FEM) using the commercial software COMSOL Multiphysics®. The insertion loss in decibels of the system versus frequency is shown in Figure 5 for a plane wave of normal incidence. The window accounted for 20% of the interior wall area and had a thickness of 0.87m. The present mathematical model is shown in red. To maintain an incident plane wave in COMSOL, a waveguide was constructed, which approximated half-space. Due to limitations on plane wave boundary conditions in the software, the insertion loss was calculated for two FEM models with waveguides having side dimensions of 10m (dashed line) and 4m (blue line). The present model compares well with the FEM model with 10m sides at frequencies below 30 Hz, and dips in insertion loss were consistent with the second FEM model at other frequencies. Each COMSOL simulation took 30-45 minutes to run whereas the present model took 1-2 seconds for frequencies 0-80Hz on a Dell computer with a 2.66 GHz dual core Intel processor and 2 GB of RAM.

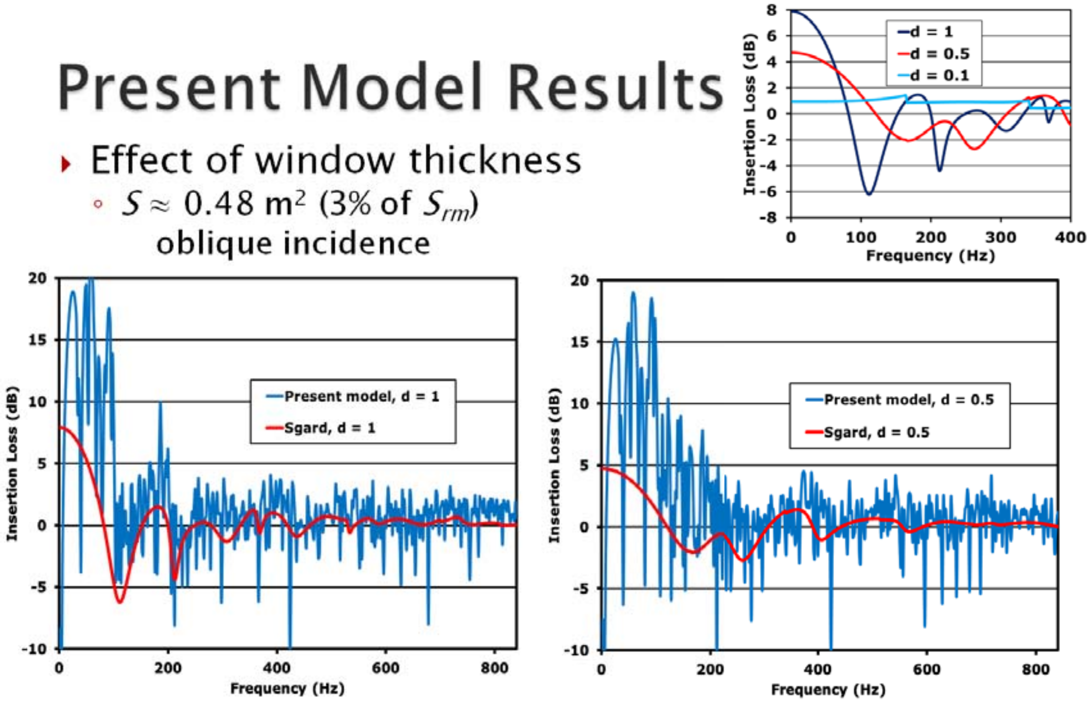


Model Verification

- Comparison between COMSOL and present model:
  - $S \approx 3.2$ m^2 (20% of S_{rm}), $d \approx 0.87$ m, normal incidence
  - FEM challenges: plane wave, time

Figure 5. Comparison of insertion loss calculations for the system by present mathematical model and FEM models

In Figure 6, the insertion loss of the present system was compared to Sgard's result for windows of varying thickness and an obliquely incident plane wave. Recall, Sgard *et al.*[8] modeled an aperture with half-space on each side. The plot in the upper right shows the insertion loss of an aperture versus frequency for aperture thicknesses of 1m, 0.5m, and 0.1m using Sgard's model. As frequency increases, the insertion loss for each case tends to zero. Also, aperture modal effects are more defined for thicker apertures. In the lower plots of Figure 6, the insertion loss calculated by Sgard's method (red) is plotted with the insertion loss of the present model (blue) for window thicknesses of 1m and 0.5m, left and right, respectively. Comparing these plots at frequencies below 300Hz reveals that the window acts as a filter for the response of the overall system. Therefore, the thickness of the window should be considered in modeling.

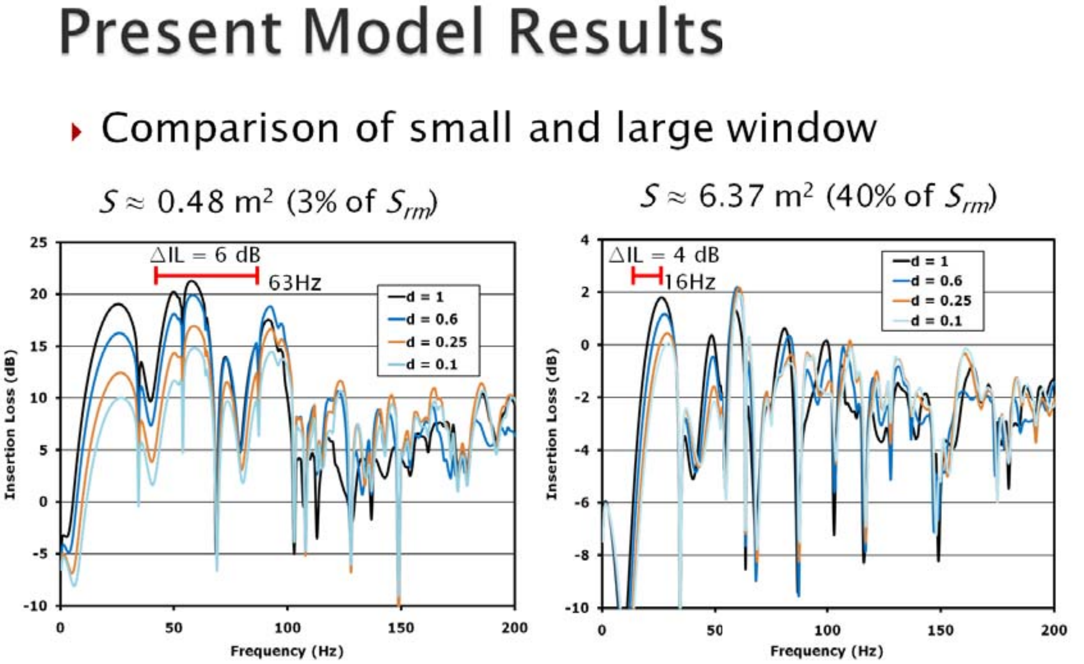


Present Model Results

- Effect of window thickness
  - $S \approx 0.48$ m^2 (3% of S_{rm}) oblique incidence

Figure 6. Filtering effect of window thickness on the insertion loss of the system

Figure 7 presents the effect of increasing the thickness of a small and large window, left and right, respectively. Increasing window thickness from 0.1m to 1m resulted in an increase in insertion loss of 6dB in the 63Hz octave band for the small window (left) and 4dB in the 16Hz octave band for the large window (right). Above these octave bands, increasing the thickness of the window had no noticeable effect on the insertion loss.



Present Model Results

- Comparison of small and large window

$S \approx 0.48$ m^2 (3% of S_{rm})

$S \approx 6.37$ m^2 (40% of S_{rm})

Figure 7. Effect of window thickness on insertion loss for two windows with different cross-sectional areas

In summary, an efficient mathematical model was developed to calculate the insertion loss of an open window backed by a room for low and mid-frequencies. This model can be easily altered to accommodate other sources and geometries and is more time efficient than FEM. Simulations showed that the response of the open window to incident sound filters the insertion loss of the overall system. Also, increasing the window thickness resulted in an increase in insertion loss at low frequencies.

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